

## Precision Measurements of Solar Energetic Particle Elemental Composition

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### 1. Introduction

Using data from the Cosmic Ray Subsystem (CRS) aboard the Voyager 1 and 2 spacecraft (Stone et al. 1977), we have determined solar energetic particle abundances or upper limits for all elements with  $3 \leq Z \leq 30$  from a combined set of 10 solar flares during the 1977-1982 time period. Statistically meaningful abundances have been determined for the first time for several rare elements including P, Cl, K, Ti and Mn, while the precision of the mean abundances for the more abundant elements has been improved by typically a factor of  $\sim 3$  over previously reported values. When compared to solar photospheric spectroscopic abundances, these new SEP abundances more clearly exhibit the step-function dependence on first ionization potential previously reported by Cook et al. (1979, 1984) and Meyer (1981, 1985).

### 2. Observations

Each CRS includes four Low Energy Telescopes (LET) and two High Energy Telescopes (HET) employing silicon solid-state detectors and covering a combined incident energy range for oxygen of 3.5 - 50 MeV/nucleon. A scatterplot of LET data from the  $Z = 14 - 20$  charge range is shown in Fig. 1. Even relatively rare elements such as Ar and Ca are clearly resolved. For the rarer elements (e.g., P, Cl, K), the abundances were determined by performing maximum-likelihood fits to the rare element peak and its two usually more abundant neighbors. For the most abundant elements (C, N, O, Ne, Na, Mg, Al, Si, S, Ar, Ca, Cr, Fe), the abundances could be determined in each of the flares; these values were averaged to obtain mean abundances using a weighting technique that takes into account both statistical variations and real abundance variations from flare to flare.

### 3. Results

The average SEP abundances relative to silicon for elements with  $3 \leq Z \leq 30$  are listed in Table I. In Fig. 2, these results for the more abundant elements are compared to those obtained by other recent investigations. It can be seen that the new abundances agree well with the previously determined values but have about a factor of three higher precision.

### 4. Discussion

An ordering by first ionization potential (FIP) of SEP composition relative to "solar system" or photospheric composition has been noted in the past (Hovestadt 1974; Webber 1975; McGuire et al. 1979). In particular, Cook et al. (1979, 1984) found a step-function dependence on FIP, with elements with  $FIP > 10$  eV depleted by a factor of  $\sim 5$  in SEPs and elements with  $FIP < 8$  eV approximately equally abundant in SEPs and the photosphere. This behavior may be expected on the basis of

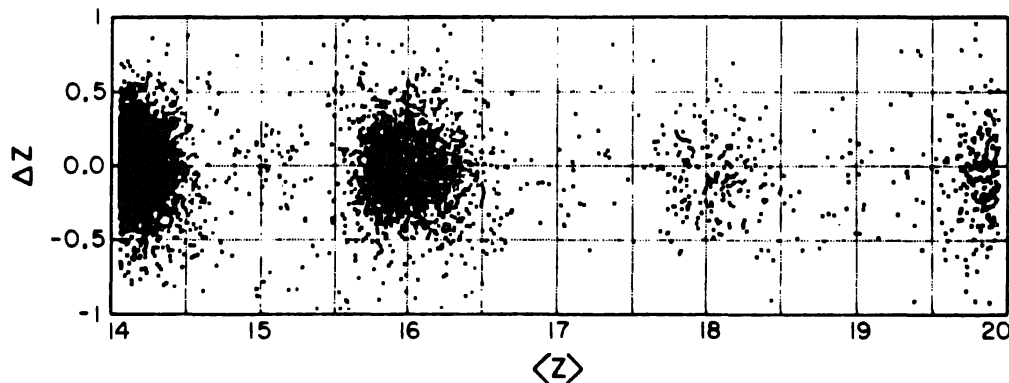


Fig. 1. Scatterplot of SEP data from LET in the  $Z = 14 - 20$  charge range.  $\langle Z \rangle$  is the average, and  $\Delta Z$  the difference, of two essentially independent charge determinations obtained from the LET data for each analyzed particle.

dynamical ionization models such as that of Geiss and Bochsler (1984) for the formation of the corona. Fig. 3 shows that the step-function ordering by FIP is more clearly defined in the new data, including the elements P, Cl, K, Ti, and Mn. However, Fig. 3 also discloses statistically significant enhancements and depletions of several elements such as Na, Fe and Ni, which are discussed by Breneman and Stone (1985) in the context of an acceleration/propagation fractionation of SEPs based on the ionic charge-to-mass ratio of the species making up the SEPs.

In Fig. 4, the SEP abundances are compared to galactic cosmic ray source (GCRS) abundances (Lund 1984). The absence of a FIP-dependence in the SEP/GCRS ratio indicates that the GCRS may have a FIP-dependent step-function fractionation like that of the SEPs (Cook et al. 1979, Meyer 1981, Lund 1984). Both may exhibit a depletion of elements with FIP greater than  $\sim 10$  eV because of the smaller flux of ionizing photons with energies greater than that of  $\text{Ly-}\alpha$  (10.2 eV). Both C and N appear to be distinctly different in SEPs and the GCRS.

Table I. SEP average elemental abundances (Si = 1000).

Z	abundance	Z	abundance	Z	abundance	Z	abundance
3	$< 1.36$	10	$887.^{+81}_{-85}$	17	$2.01^{+0.83}_{-0.82}$	24	$14.3^{+2.9}_{-2.4}$
4	$< 0.17$	11	$73.3^{+7.2}_{-6.6}$	18	$20.7^{+3.5}_{-3.0}$	25	$5.0^{+2.7}_{-1.9}$
5	$< 0.34$	12	$1206.^{+84}_{-81}$	19	$2.95^{+1.01}_{-0.93}$	26	$959.^{+105}_{-94}$
6	$2710.^{+270}_{-240}$	13	$87.4^{+4.3}_{-4.1}$	20	$68.^{+12}_{-10}$	27	$< 13.5$
7	$775.^{+54}_{-51}$	14	1000.	21	$(0.22^{+0.38}_{-0.22})^*$	28	$33.6^{+8.0}_{-5.3}$
8	$6230.^{+380}_{-340}$	15	$4.78^{+0.84}_{-0.70}$	22	$3.5^{+1.4}_{-1.1}$	29	$(0.40^{+0.64}_{-0.40})^*$
9	$(0.29^{+0.29}_{-0.25})^*$	16	$222.^{+8}_{-7}$	23	$(0.34^{+0.48}_{-0.34})^*$	30	$1.09^{+0.92}_{-0.83}$

\* Abundances for these elements are based on fewer than 5 particles and are highly uncertain.